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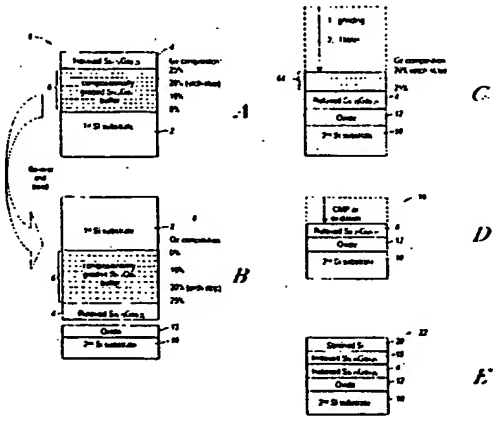

(57) Abstract: A method of fabricating a semiconductor structure. According to one aspect of the invention, on a first semiconductor substrate, a first compositionally graded $Si_{1-x}Ge_x$ buffer is deposited where the Ge composition x is increasing from about zero to a value less than about 20%. Then a first etch-stop $Si_{1-y}Ge_y$ layer is deposited where the Ge composition y is larger than about 20% so that the layer is an effective etch-stop. A second etch-stop layer of strained Si is then grown. The deposited layer is bonded to a second substrate. After that the first substrate is removed to release said first etch-stop $Si_{1-y}Ge_y$ layer. The remaining structure is then removed in another step to release the second etch-stop layer. According to another aspect of the invention, a semiconductor structure is provided. The structure has a layer in which semiconductor devices are to be formed. The semiconductor structure includes a substrate, an insulating layer, a relaxed SiGe layer where the Ge composition is larger than approximately 15%, and a device layer selected from a group consisting of, but not limited to, strained-Si, relaxed $Si_{1-y}Ge_y$ layer, strained $Si_{1-z}Ge_z$ layer, Ge, GaAs, III-V materials, and II-IV materials, where Ge compositions y and z are values between 0 and 1.

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A METHOD FOR SEMICONDUCTOR DEVICE FABRICATION

PRIORITY INFORMATION

This application claims priority from provisional application Ser. No. 60/281,502 filed April 4, 2001.

BACKGROUND OF THE INVENTION

The invention relates to the production of a general semiconductor substrate of relaxed $Si_{1-x}Ge_x$-on-insulator (SGOI) for various electronics or optoelectronics applications, the production of strained Si or strained SiGe field effect transistor (FET) devices on SGOI, and the production of monocrystalline III-V or II-VI material-on-insulator substrates.

Relaxed SGOI is a very promising technology as it combines the benefits of two advanced technologies: the conventional SOI technology and the disruptive SiGe technology. The SOI configuration offers various advantages associated with the insulating substrate, namely reduced parasitic capacitances, improved isolation, reduced short-channel-effect, etc. The SiGe technology also has various advantages, such as mobility enhancement and integration with III-V devices.

One significant advantage of the relaxed SGOI substrate, is to fabricate high mobility strained-Si, strained-$Si_{1-x}Ge_x$ or strained-Ge FET devices. For example, strained-Si MOSFETs can be made on the SGOI substrate. The strained-Si MOSFETs on the SGOI has attracted attention because it promises very high electron and hole mobilities, which increase the speed of the electronic circuit. Other III-V optoelectronic devices can also be integrated into the SGOI substrate by matching the lattice constants of III-V materials and the relaxed $Si_{1-x}Ge_x$. For example, a GaAs layer can be grown on $Si_{1-x}Ge_x$-on-insulator where x is equal or close to 1. SGOI may serve as an ultimate platform for high speed, low power electronic and optoelectronic applications.

There are several methods for fabricating SGOI substrates and SGOI FET devices. In one method, the separation by implantation of oxygen (SIMOX) technology is used to produce SGOI. SIMOX uses a high dose oxygen implant to bury a high concentration of oxygen in a $Si_{1-x}Ge_x$ layer, which will then be converted into a buried oxide (BOX) layer upon annealing at a high temperature. One of the main drawbacks is the quality of the resulting $Si_{1-x}Ge_x$ film and the BOX layer. In addition, the Ge segregation during the high temperature anneal also limits the amount of Ge composition to a value that is low, such as 10%. Due to the low Ge composition, the device

fabricated on those SGOI substrates has limited performance. For example. the strained-Si MOSFETs fabricated on the SGOI by the SIMOX process have limited electron or hole mobility enhancement due to the low Ge composition, since the mobility enhancement is dependent on Ge composition through the degree of the strain in the strained-Si layer.

In a second method, a conventional silicon-on-insulator (SOI) substrate is used as a compliant substrate. In this process, an initially strained $Si_{1-x}Ge_x$ layer is deposited on a thin SOI substrate. Upon an anneal treatment, the strain in the $Si_{1-x}Ge_x$ layer is transferred to the thin silicon film underneath, resulting in relaxation of the top $Si_{1-x}Ge_x$ film. The final structure is a relaxed-SiGe/strained-Si/insulator. The silicon layer in the structure is unnecessary for an ideal SGOI structure, and may complicate or undermine the performance of devices built on it. For example, it may form a parasitic back channel on the strained-Si, or may confine unwanted electrons due to the band gap offset between the strained-Si and SiGe layer.

In a third method, a similar SGOI substrate is produced using a p^{++} layer as an etch stop. On a first Si substrate, a compositionally graded SiGe buffer is deposited, followed by deposition of multiple material layers including a relaxed SiGe layer, a p^{++} etch stop layer, and a Si layer. After bonding to a second substrate, the first substrate is removed. In an etching process, the compositionally graded SiGe buffer is etched away and etching stops at P^{++} etch stop layer, resulting in a relaxed-SiGe/Si/insulator structure. The presence of the silicon layer in the structure may be for the purpose of facilitating the wafer bonding process, but is unnecessary for ideal SGOI substrates. Again, the silicon layer may also complicate or undermine the performance of devices built on it. For example, it may form a parasitic back channel on this strained-Si, or may confine unwanted electrons due to the band gap offset between the Si and SiGe layer. Moreover, the etch stop of p^{++} in the above structure is not practical when a first graded $Si_{1-y}Ge_y$ layer has a final y value larger than 0.2. This is because the etch rate of KOH will slow down dramatically when KOH reaches the $Si_{1-y}Ge_y$ layer with a Ge composition larger than 0.2, and that layer is itself a very good etch stop for KOH. Therefore, KOH will not be able to remove practically all of the first compositionally graded $Si_{1-y}Ge_y$ layer (when y is larger than 0.2) and the second relaxed SiGe layer, thus using a p^{++} layer as an etch-stop for KOH is not practical.

Other attempts include re-crystallization of an amorphous $Si_{1-x}Ge_x$ layer deposited on the top of a SOI (silicon-on-insulator) substrate. Again, such a structure is

not an ideal SGOI substrate and the silicon layer is unnecessary, and may complicate or undermine the performance of devices built on it. The relaxation of the resultant SiGe film and quality of the resulting structure are main concerns.

In a recent method, relaxed $Si_{1-x}Ge_x$-on-insulator is produced by using 20% SiGe layer as an etch-stop. First a compositionally graded $Si_{1-x}Ge_x$ buffer (where x is less than about 0.2) and then a uniform $Si_{1-y}Ge_y$ etch-stop layer (where y is larger than about 0.2) are deposited on the first substrate. Then the deposited layer is bonded to a second insulating substrate. After removing the first substrate and graded buffer layer utilizing the $Si_{1-y}Ge_y$ as an etch-stop, a $Si_{1-y}Ge_y$-on-insulator (SGOI) results. The method makes use of an experimental discovery that $Si_{1-y}Ge_y$ with Ge composition larger than about 20% is a good etch-stop for all three conventional Si etchant systems, KOH, TMAH and EDP, and the selectivity is better than the conventional p^{++} etch stop. In this method the etch-stop $Si_{1-y}Ge_y$ layer is part of the final SGOI structure. However, as the Ge composition in the final SGOI structure is fixed by the etch-stop $Si_{1-y}Ge_y$, if the desired Ge composition in the final SGOI structure is much higher or lower than 0.2, the above method is not practical. If it is much lower than 0.2, for example 0.1, $Si_{0.9}Ge_{0.1}$ is not a good etch stop at all. If it is much larger than 0.2, the Ge composition difference between the etch-stop layer and surface layer in the grade buffer is too big and there is large lattice constant difference between the two layers, which prevents the growth of a relaxed etch-stop $Si_{1-y}Ge_y$ layer with good quality.

From above, clearly an improved method is needed to fabricate a relaxed SGOI substrate with high Ge composition and wide range of Ge composition. An improved method is needed to fabricate strained-Si or strained-SiGe FET devices on SGOI substrate with high Ge composition.

SUMMARY OF THE INVENTION

According to one aspect of the invention, the invention provides a method of semiconductor device fabrication, and more specifically, a method of production of a general semiconductor substrate of relaxed SGOI for various electronics or optoelectronics applications, a method of production of strained Si or strained SiGe FET devices on SGOI, and the production of monocrystalline III-V or II-VI material-on-insulator substrates. The invention provides a method of producing a relaxed $Si_{1-x}Ge_x$-on-insulator substrate with high Ge composition and wide range of Ge composition, and the Ge composition may be much less or much higher than 20%. The invention provides an improved method to fabricate

strained-Si or strained-SiGe MOSFET devices on SGOI substrate with high Ge composition. When strained-Si n-MOSFETs are fabricated on relaxed $Si_{1-x}Ge_x$-on-insulators substrates with a high Ge composition, 25% for example, there is significant enhancement on electron mobility as compared to the co-processed bulk-Si MOSFETs on conventional bulk Si substrate.

BRIEF DESCRIPTION OF THE DRAWINGS

Figs. 1(a)-1(d) are flow process diagrams of a SGOI substrate fabrication process;

Fig. 1(e) is a block diagram of relaxed SiGe and strained-Si regrowth on a relaxed SGOI substrate for strained-Si MOSFET application;

Fig. 2 is a block diagram of a compositionally graded $Si_{1-x}Ge_x$ buffer deposited epitaxially on a Si substrate;

Fig. 3 is a micro-photograph of an exemplary strained-Si surface channel MOSFET device fabricated on relaxed $Si_{0.75}Ge_{0.25}$-on-insulator;

Fig. 4 is a graph showing the measured experimental effective electron mobility as a function of effective vertical electric field from the exemplary strained-Si MOSFET device shown in Fig. 3 ;

Fig. 5 is a block diagram of another embodiment of a of SGOI structure with 10% Ge;

Fig. 6 is a block diagram of another embodiment of a SGOI structure with 80% Ge using two etch-stops;

Fig. 7 is a block diagram showing the production of an III-V on insulator structures; and

Fig. 8 is a block diagram of another embodiment of a SGOI structure with improved SiGe layer thickness uniformity.

DETAILED DESCRIPTION OF THE INVENTION

Figs. 1(a)-1(d) are flow process diagrams of an experimental fabrication process of a SGOI substrate with Ge composition of 25% in accordance with one embodiment of the invention. Starting with a 4-inch Si (100) substrate 2, high quality relaxed $Si_{0.75}Ge_{0.25}$ layer 4 is grown at 900 °C by UHVCVD using a compositionally graded $Si_{1-x}Ge_x$ buffer 6 technique as described in U.S. Pat. No. 5,221,413 issued to Brasen et al., which is incorporated herein by reference in its entirety. Using this technique, a compositionally graded $Si_{1-x}Ge_x$ buffer 6 can be grown epitaxially on Si substrate, which allows a relaxed SiGe layer to be grown on the top of the buffer with low threading dislocation density.

Fig. 2. is a block diagram of a compositionally graded $Si_{1-x}Ge_x$ buffer 30. The compositionally graded $Si_{1-x}Ge_x$ buffer 30 is a multi-layer structure where the Ge composition in each layer is changing gradually from a beginning value to a final value. For example, the compositionally graded $Si_{1-x}Ge_x$ buffer 30 shown in Fig. 2 has 16 layers, and the Ge composition x in the first layer is 0% and is increasing gradually to 2%, 4%, 6% until 30% in the last layer (layer 16). Such a compositionally graded $Si_{1-x}Ge_x$ buffer 30 allows a high quality relaxed $Si_{0.7}Ge_{0.3}$ layer to be grown on the top of the buffer with low threading dislocation density.

Referring to Figs. 1(a)-1(d), a compositionally graded $Si_{1-x}Ge_x$ buffer 6 is epitaxially grown on a 4-inch Si (100) substrate 2, where the Ge composition x is increasing gradually from zero to 25% with a grading rate of 10% Ge/μm. Within the compositionally graded $Si_{1-x}Ge_x$ buffer 6, a portion of the buffer 6 with Ge composition larger than about 20% forms a natural etch stop. A 2.5 μm-thick undoped, relaxed $Si_{0.75}Ge_{0.25}$ cap layer 4 is then deposited, as shown in Fig. 1(a). The slow grading rate and high growth temperature result in a completely relaxed cap layer 4 with threading dislocation densities of $\sim 10^5$ cm^{-2}. As shown in Fig. 1(b), the wafer 2 is then flipped over and bonded to a second Si substrate 10, which is thermally oxidized. The oxide 12 in the second substrate will become the insulator layer in the final SiGe-on-insulator substrate. The bonded pair is then annealed at 850 °C for 1.5 hrs. The bonded pair is grounded to remove the donor wafer substrate 8, as shown in Fig. 1(c). The wafer 8 is then subjected to a TMAH solution to etch away a portion of the compositionally graded $Si_{1-x}Ge_x$ buffer 6 with Ge composition less than 20%. The etching process stops approximately at a 20% SiGe layer 14 within the compositionally graded $Si_{1-x}Ge_x$ buffer 6 and the 20% SiGe layer 14 is used as a natural etch stop.

After performing the etching process, the remaining portion of the compositionally graded $Si_{1-x}Ge_x$ buffer 14 with a Ge composition between 20% to 25% and part of the relaxed $Si_{0.75}Ge_{0.25}$ layer 4 are removed by chemical-mechanical polishing (CMP), resulting in a relaxed $Si_{0.75}Ge_{0.25}$-on-insulator substrate, as shown in Fig. 1(d). The CMP process is also essential in planarizing the SGOI surface for epitaxial regrowth in the next step. As shown in Fig. 1(e), in order to make a strained-Si device 22, a 100 nm p-type (doping 10^{16} cm^{-3}) relaxed $Si_{1-x}Ge_x$ layer 18 is grown at 850 °C with a Ge composition of 25%, followed by 8.5 nm-thick undoped strained-Si layer 20 grown at 650°C. Electronic devices may be fabricated on the above semiconductor structure. In particular, a large size strained-Si *n*-MOSFETs can be fabricated on the above structure and significant electron mobility enhancement is observed from the strained-Si MOSFETs.

Fig. 3 is a micro-photograph of a strained-Si, surface channel *n*-MOSFETs on the relaxed SGOI substrate. The *n*-MOSFET includes gate stack 24 that has a 300 nm low temperature oxide (LTO) 26 deposited via LPCVD at 400°C, and a 50 nm of poly-Si 28 deposited at 560°C. The large thickness of the LTO gate 24 dielectric facilitates the process, as described below. Capacitors fabricated with LTO have demonstrated interface state densities on par with thermal oxides (~5×10^{10} cm^{-2} eV^{-1}). The measured fixed oxide charge density is about 2.4×10^{11} cm^{-2}.

The gate stack 24 is then patterned and etched into MOSFET structures. A key step is the use of a buffered oxide etchant (BOE) to undercut the gate polysilicon, forming a large "T-gate" geometry. Arsenic ion implants (35 keV, total dose 1×10^{15} cm^{-2}) are performed to dope both the source/drain 30 and gate 24 regions at 4 perpendicular directions with a 7° tilt to extend the source/drain regions under the T-gate structure. The dopant is activated via RTA at 1000°C for 1 s. Since the strained-Si layer 32 is in equilibrium, no relaxation via misfit dislocation introduction occurred. Blanket Ti/Al metallization is performed via e-beam deposition at a perpendicular incidence. Due to the extreme geometry of the "T-gate" FET structure and large gate LTO 26 thickness, breaks occur in the metal which isolate the source, gate, and drain regions 24 and 30 without further lithography.

Long channel *n*-MOSFETs (effective channel length L_{eff} = 200 μm) are used to evaluate the electron mobility as a function of the vertical field. The effective electron mobility μ_{eff} is extracted from the linear regime device current that is defined as:

$$\mu_{eff} = (L_{eff}/W_{eff})\, I_{DS} / [C_{ox}(V_{GS}-V_T)V_{DS}], \qquad \text{Eq. 1}$$

where L_{eff} is effective channel length, W_{eff} is effective channel width, I_{DS} is current from the drain to source, C_{ox} is the oxide capacitance, V_{GS} is gate to source voltage, V_{DS} is the drain to source voltage, wherein in this embodiment, V_{DS} = 0.1 V. The oxide capacitance is defined as

$$C_{ox} = \varepsilon_{ox} / t_{ox} \qquad \text{Eq. 2}$$

where ε_{ox} is the dielectric constant of oxide, and t_{ox} is the oxide thickness. The oxide capacitance is obtained from C-V measurements on the device, and the oxide thickness t_{ox} = 326 nm is also extracted from the C-V measurements. The effective vertical field E_{eff} is given by

$$E_{eff} = (Q_b + Q_{inv}/2)/\varepsilon_S. \qquad \text{Eq. 3}$$

where Q_b is the bulk depletion charge, Q_{inv} is the inversion charge, and ε_S is the dielectric constant of Si. Because of uncertainties in the strained-Si/$Si_{0.75}Ge_{0.25}$ doping, the bulk depletion charge Q_b is not computed from the usual $N_A x_{d,max}$ approximation. Instead, Q_b is extracted from

$$E_{ox}\varepsilon_{ox} = Q_{inv} + Q_b, \quad \text{Eq. 4}$$

where E_{ox} is the electric field in the gate oxide. As a result, the effective field can be approximated by

$$E_{eff} = [E_{ox}\varepsilon_{ox} - Q_{inv}/2] / \varepsilon_s. \quad \text{Eq. 5}$$

The inversion charge Q_{inv} is taken to be

$$C_{ox}(V_{GS}-V_T).E_{ox} \quad \text{Eq. 6}$$

and is assumed to be equal to V_{GS}/t_{ox}, which holds under the conditions of strong inversion and $V_{GS} >> V_{DS}$, such that the potential difference between the strongly-inverted Si surface and the S/D regions is negligibly small compared with the large potential drop across the thick gate oxide.

Fig. 4 is a graph demonstrating the measured effective electron mobility as a function of the effective vertical electric field on a strained-Si on SGOI. The graph also demonstrates the mobilities of two other controls, such as conventional bulk Si MOSFETs 34 and strained-Si MOSFETs 38 on relaxed bulk SiGe substrate, for comparison. Since all three devices have the same geometry and are processed simultaneously, possible errors due to factors such as the extraction of the ring geometry factor, and approximations in E_{eff} evaluation do not impact the relative comparison of the electron mobility characteristics. As shown in Fig. 4 , the measured mobility for the CZ Si control device 34 is close to the universal mobility curve 40. Fig. 4 also shows that the measured electron mobility enhancement for strained Si MOSFETs 36 fabricated on SGOI as compared to the mobility of co-processed bulk Si MOSFETs 38 is significant (~1.7 times). In addition, the electron mobilities are comparable for devices fabricated on SGOI 36 and bulk relaxed SiGe layers 38, thus demonstrating the superior mobility performance introduced by the strained-Si channel is retained in this SGOI structure. This enhancement factor of 1.7 is consistent with previously reported experimental and theoretical values for strained-Si *n*-MOSFETs on bulk relaxed SiGe films.

This demonstrates that the fabrication of relaxed SGOI structures and strained-Si FET devices on SGOI with high Ge composition of 25% is practical. This also demonstrates that strained-Si MOSFETs fabricated on a SGOI substrate can significantly

improve electron mobility. In contrast to the method of fabrication of SGOI by SIMOX process where the high annealing temperature limits the Ge composition to a low value, the process of forming a SGOI in accordance with the invention has a low thermal budget and thus is compatible with a wide range of Ge composition in the SGOI substrate. This embodiment of invention allows fabrication of a SGOI substrate and a strained-Si FET device with high Ge composition, and the Ge composition can be much higher than the Ge composition in the relaxed $Si_{1-y}Ge_y$ etch-stop layer where y has a value close to 20%.

In a variation of the above process, before the step of bonding, various of material layers like strained-Si, strained-SiGe, relaxed SiGe may also grown on the relaxed $Si_{0.75}Ge_{0.25}$ cap layer 4. For example, a three layer system, a strained-Si, a strained-SiGe and a relaxed SiGe layer, may be deposited before bonding. Therefore, after bonding and layer removal steps, the strained-Si and strained-SiGe layers are on the SGOI structure and can be used to fabricate both n-MOSFET and p-MOSFET devices immediately without a regrowth step.

Fig. 5 is a block diagram of a low Ge composition SGOI substrate. The Ge composition in the SGOI substrate can be considerably less than the Ge composition in a relaxed $Si_{1-y}Ge_y$ etch-stop layer where y has a value close to 20%. For example, a SGOI substrate with Ge composition of 10% can be fabricated. As shown in Fig. 5, a compositionally graded $Si_{1-x}Ge_x$ buffer 46 is epitaxially grown on a silicon substrate 44, where the Ge composition x is increasing gradually from about zero to about 20%. A uniform etch-stop layer 48 of relaxed $Si_{1-y}Ge_y$ is deposited where Ge composition y is larger than or close to about 20%. Then a second compositionally graded $Si_{1-z}Ge_z$ buffer 50 is grown on the etch-stop layer 48 where Ge composition z is decreasing gradually from a value close to 20% to a smaller value, in this embodiment 10%. Finally a uniform relaxed $Si_{0.9}e_{0.1}$ layer 52 is grown.

After flipping over and bonding to a second substrate, the first substrate is removed. A wet etch of KOH or TMAH removes the first graded buffer and stops at the etch-stop layer 48. After the etch-stop layer 48 and second compositionally graded $Si_{1-z}Ge_z$ buffer 50 are removed, the relaxed $Si_{0.9}Ge_{0.1}$ layer 52 is released, resulting in a $Si_{0.9}Ge_{0.1}$-on-insulator substrate. In summary, this process allows the production of SGOI with Ge composition much less than 20%.

The embodiment outlined in Fig. 1 is also applicable to the fabrication of SGOI structures with very high Ge composition, for example 80%. However, the $Si_{0.2}Ge_{0.8}$ layer in the final SGOI structure may not have good thickness uniformity for such high Ge

composition. The SiGe layer thickness uniformity is important. For example, to fabricate strained-Si MOSFET devices on a SGOI structure, the performance of the devices strongly depends on the thickness of the $Si_{0.2}Ge_{0.8}$ layer. A uniform SiGe layer is highly desired. To fabricate SGOI with Ge composition of 80% using the method described in Fig. 1, it necessitates the deposition of a relative thick compositionally graded $Si_{1-x}Ge_x$ buffer where the Ge composition is increasing gradually from zero to 80%. A TMAH or KOH etch step etches away the portion of the compositionally graded $Si_{1-x}Ge_x$ buffer where Ge composition is less than 20% and stops at 20% SiGe layer within the compositionally graded $Si_{1-x}Ge_x$ buffer. The remaining portion of the compositionally graded $Si_{1-x}Ge_x$ buffer is still considerably thick, where Ge composition varies from about 20% to 80%. For example, the remaining portion of the compositionally graded $Si_{1-x}Ge_x$ buffer with Ge composition from 20% to 80% has a thickness of 6 μm if the buffer is grown with a grading rate of 10% Ge/μm.

This 6 μm thick buffer needs to be removed in order to explore the $Si_{0.2}Ge_{0.8}$ layer, for example by means of CMP. This removing step may induce significant non-uniformity. There are two possible sources of non-uniformity. First, the growth of the SiGe film itself may be not uniform across the whole substrate. For example, it is observed that the SiGe buffer can vary more than 10% in thickness if the surface of the Si substrate is placed in parallel to the direction of reactant gas flow in the CVD reactor during growth. In this orientation, one part of the substrate is in contact with higher concentration of gas than the other part since the gas concentration is decreasing along its flow pass as gas gets consumed. Therefore, the growth rate is different, resulting in differences of layer thickness. To avoid this non-uniformity, it is preferred that the surface of the Si substrate be placed normal to the direction of reactant gas flow in the reactor during the growth.

The second source comes from the removing process of the buffer layer. For example, if the buffer layer is removed by a polishing technique such as CMP, the CMP process may induce some uniformity. Although the CMP can improve the local uniformity, it may induce some global non-uniformity across the wafer. For example, the CMP process may polish the edge of the wafer faster than the center. As a result, the final SGOI structure has a non-uniform SiGe layer. Using two or more etch-stops, the system can improve the uniformity as described in the embodiment below.

Fig. 6 is block diagram of a SGOI substrate with improved SiGe layer uniformity using two etch stop layers, which is especially suitable for SGOI substrates with high Ge composition. As shown in Fig. 6, a compositionally graded $Si_{1-x}Ge_x$ buffer 56 is grown on a

silicon substrate 54, where Ge composition x is increasing gradually from zero to about 0.2. A uniform etch-stop layer 60 of $Si_{0.8}Ge_{0.2}$ is deposited, and then a continuing compositionally graded $Si_{1-y}Ge_y$ buffer 62 is provided where Ge composition y is increasing gradually from about 0.2 to a higher value, for example 0.8. A second etch-stop layer 64 of strained-Si is then grown. A uniform $Si_{0.2}Ge_{0.8}$ layer 66 is deposited with a Ge composition of 80%. After flipping over and bonding to a second insulating substrate, the first substrate is removed. During a first etching step, the first compositionally graded $Si_{1-x}Ge_x$ buffer 56 is removed and the etching stops at the first etch-stop layer 60 of $Si_{0.8}Ge_{0.2}$. With another etching step, the second compositionally graded $Si_{1-y}Ge_y$ buffer 62 is removed and the etching stops at the second etch-stop layer 64 of strained-Si. Removing the second etch-stop layer 64, the final relaxed $Si_{0.2}Ge_{0.8}$ layer 66 is released, resulting in a $Si_{0.2}Ge_{0.8}$-on-insulator substrate. { In the above process, the surface of the deposited layers may be very rough due to the crosshatch in the SiGe buffer. A smoother strained-Si and relaxed SiGe layer may be wanted. A CMP step can be used for this purpose to smooth for example the compositionally graded $Si_{1-y}Ge_y$ buffer 62, before depositing the second etch-stop layer 64.

Fig. 7 is a block diagram of a GaAs-on-insulator substrate. As shown in Fig. 7, a compositionally graded $Si_{1-x}Ge_x$ buffer 74 is grown on a silicon substrate 72, where Ge composition x is increasing gradually from zero to about 1, i.e., to pure Ge composition. Within the compositionally graded $Si_{1-x}Ge_x$ buffer, a portion of the buffer with Ge composition larger than about 20% forms a natural SiGe etch stop. Then a second etch-stop layer 76 of strained-Si is grown, followed by a relaxed Ge layer 78. A uniform GaAs layer 80 is then deposited. After flipping over and bonding to a second insulating substrate, the first substrate is removed. During the first etching step, the portion of the compositionally graded $Si_{1-x}Ge_x$ buffer 74 with Ge composition smaller than 20% is removed and the etching stops at the first etch-stop layer. With the second etching step, the remaining compositionally graded $Si_{1-x}Ge_x$ buffer 74 is removed and the etching stops at the second etch-stop layer 76 of strained-Si. Removing the second etch-stop layer 76 of strained-Si and the Ge layer 78 results in a GaAs-on-insulator structure.

In all of the above-mentioned SGOI or GaAs-on-insulator fabrication processes, wafer bonding is used. In order to bond two surfaces, the surfaces should be smooth enough, with a very small surface roughness. However, the as-grown SiGe layer, strained Si layer, Ge layer or GaAs layer can be rough. Typically, the compositionally graded SiGe buffer shows a very rough surface due to the cross-hatch (a dislocation-induced phenomenon). The CMP process is conventionally used to smooth the surface before

bonding. However, as described above, CMP may induce global non-uniformity across the wafer. Moreover, in some cases, there may not be enough thickness for a surface to be polished. For example, if a layer is a strained Si etch-stop layer, its thickness is very small in order to keep it strained without relaxation, for example 10 nm.

Two approaches may be used to solve this issue. The first approach is before depositing the last thin material layer (e.g., the last layer is a strained Si layer), polish the SiGe buffer layer to achieve enough surface smoothness. Then grow the last strained Si etch-stop layer, which results in a smoother final surface. If the surface is smooth enough, the structure can be bonded directly. Even if polishing is still needed, it will reduce the thickness to be polished.

The second approach requires before bonding to deposit an additional insulating material layer like an oxide layer on the first structure. Afterward, polish this additional insulating layer to achieve enough surface smoothness, and then bond the polished insulating layer to a second substrate.

Fig. 8 is a block diagram of a $Si_{0.8}Ge_{0.2}$-on-insulator substrate with improved $Si_{0.8}Ge_{0.2}$ layer uniformity. As shown in Fig. 8, a compositionally graded $Si_{1-x}Ge_x$ buffer 84 is grown on a silicon substrate 82, where Ge composition x is increasing gradually from zero to about 20%. Then a $Si_{0.8}Ge_{0.2}$ etch-stop layer 86 with selected thickness is deposited. The $Si_{0.8}Ge_{0.2}$ etch-stop layer 86 will also contribute to the SiGe layer in the final $Si_{0.8}Ge_{0.2}$-on-insulator substrate. The thickness of the $Si_{0.8}Ge_{0.2}$ etch-stop layer 86 is thick enough to sustain the selective etch process. This thickness is also chosen deliberately such that the resulting final $Si_{0.8}Ge_{0.2}$-on-insulator substrate has a desired $Si_{0.8}Ge_{0.2}$ layer thickness. For example, for the purpose of fabricating high mobility strained-Si MOSFET on $Si_{0.8}Ge_{0.2}$-on-insulator substrate, a final $Si_{0.8}Ge_{0.2}$ layer 86 thickness of 100 nm or less may be desired. After the deposition of $Si_{0.8}Ge_{0.2}$ etch-stop layer 86, an additional insulating layer is deposited, for example an oxide layer 88. The oxide layer 88 is polished by CMP to achieve surface smoothness required by wafer bonding. By doing this, the polishing of $Si_{0.8}Ge_{0.2}$ etch-stop layer 86 is avoided. Without the polishing step, the $Si_{0.8}Ge_{0.2}$ etch-stop layer 86 can maintain its good uniformity. After flipping over and bonding to a second substrate, the first substrate is removed. After a selective etching process with TMAH or KOH, which removes the compositionally graded $Si_{1-x}Ge_x$ buffer and stops at the $Si_{0.8}Ge_{0.2}$ etch-stop layer 86, a final $Si_{0.8}Ge_{0.2}$-on-insulator substrate results. The structure has good SiGe layer uniformity. Polishing may be used to smooth the $Si_{0.8}Ge_{0.2}$ surface after etching without

removing too much material. Then strained-Si is grown on the SGOI structure and strained-Si MOSFET may be fabricated on the SGOI with Ge composition of 20%.

Although the present invention has been shown and described with respect to several preferred embodiments thereof, various changes, omissions and additions to the form and detail thereof, may be made therein, without departing from the spirit and scope of the invention.

What is claimed is:

CLAIMS

1. A method of fabricating a semiconductor structure comprising:

providing a first semiconductor substrate;

depositing a compositionally graded $Si_{1-x}Ge_x$ buffer on said first semiconductor substrate, where the Ge composition x is increasing from about 0% to a value larger than about 20%, wherein a portion of said compositionally graded $Si_{1-x}Ge_x$ buffer with Ge composition larger than about 20% forms a natural SiGe etch-stop layer;

depositing one or more material layers selected from the group consisting of, but not limited to, relaxed $Si_{1-y}Ge_y$ layer, strained $Si_{1-z}Ge_z$ layer, strained-Si, Ge, GaAs, III-V materials, and II-VI materials, where Ge compositions y and z are values between 0 and 1.

bonding said deposited layers to a second substrate;

removing said first substrate to explore said etch-stop SiGe layer which including the portion of said compositionally graded $Si_{1-x}Ge_x$ buffer where the Ge composition is larger than approximately 20% ; and

removing said remaining portion of said compositionally graded $Si_{1-x}Ge_x$ buffer in order to release said one or more material layers.

2. The method of claim 1, wherein said second substrate has an insulating layer on the surface.

3. The method of claim 1 further comprising depositing an insulating layer before bonding.

4. The method of claim 1 further comprising polishing the surface of one of said deposited layers.

5. The method of claim 1 further comprising polishing the surface of said first substrate before bonding.

6. The method of claim 1 further comprising depositing one or more second material layers selected from the group consisting of, but not limited to, relaxed $Si_{1-y}Ge_y$ layer, strained $Si_{1-z}Ge_z$ layer, strained-Si, Ge, GaAs, III-V materials, and II-VI materials, where Ge compositions y and z are values between 0 and 1.

7. The method of claim 6 further comprising polishing the surface of said released

of said one or more material layers before depositing said one or more second material layers.

8. The method of claims 1 further comprising fabricating a semiconductor device selected from the group consisting of, but not limited to, FET device, MOSFET device, MESFET device, solar cell device, and optoelectronic device.

9. A method of fabricating a semiconductor structure comprising:

providing a first semiconductor substrate;

depositing a first compositionally graded $Si_{1-x}Ge_x$ buffer on said first semiconductor suostrate, where the Ge composition x is increasing from about zero to a value less than about 20%;

depositing a uniform etch-stop $Si_{1-y}Ge_y$ layer of with selected thickness on said compositionally graded $Si_{1-x}Ge_x$ buffer where the Ge composition y is larger than about 20%; and

depositing a second compositionally graded $Si_{1-z}Ge_z$ buffer on said uniform etch-stop $Si_{1-y}Ge_y$ layer, where the Ge composition x is decreasing from about 20% to less than 20%.

10. The method of claim 9 further comprising polishing the surface of one of said deposited layers.

11. A method of fabricating a semiconductor structure comprising:

providing a first semiconductor substrate;

depositing a first compositionally graded $Si_{1-x}Ge_x$ buffer on said first semiconductor substrate, where the Ge composition x is increasing from about zero to a value less than about 20%;

depositing a uniform etch-stop $Si_{1-y}Ge_y$ layer of with a selected thickness on said compositionally graded $Si_{1-x}Ge_x$ buffer where the Ge composition y is larger than about 20%;

depositing a second compositionally graded $Si_{1-z}Ge_z$ buffer on said uniform etch-stop $Si_{1-y}Ge_y$ layer, where the Ge composition z is decreasing from about 20% to a value less than 20%;

depositing one or more material layers selected from the group consisting of, but not limited to, relaxed $Si_{1-y}Ge_y$ layer, strained $Si_{1-z}Ge_z$ layer, where Ge compositions y and z are values between 0 and 1.

bonding said deposited layers to a second substrate;

removing said first substrate to release said uniform etch-stop $Si_{1-y}Ge_y$ layer ;

removing said uniform etch-stop $Si_{1-y}Ge_y$ layer; and

removing said second compositionally graded $Si_{1-z}Ge_z$ buffer.

12. The method of claim 11, wherein said second substrate has an insulating layer on the surface.

13. The method of claim 11 further comprising depositing an insulating layer before bonding.

14. The method of claim 11 further comprising polishing the surface of one of said deposited layers.

15. The method of claim 11 further comprising polishing the surface of said first substrate before bonding.

16. The method of claim 11 further comprising depositing one or more second material layers selected from the group consisting of, but not limited to, relaxed $Si_{1-y}Ge_y$ layer, strained $Si_{1-z}Ge_z$ layer, strained-Si, Ge, GaAs, III-V materials, and II-VI materials, where Ge compositions y and z are values between 0 and 1.

17. The method of claim 16 further comprising polishing the surface of said released of said one or more material layers before depositing said one or more second material layers.

18. The method of claims 11 further comprising fabricating a semiconductor device selected from the group consisting of, but not limited to, FET device, MOSFET device, MESFET device, solar cell device, and optoelectronic device.

19. A semiconductor etch-stop layer structure that includes a monocrystalline semiconductor substrate, said semiconductor etch-stop layer structure comprises:

a first compositionally graded $Si_{1-x}Ge_x$ buffer where the Ge composition x is increasing from about zero to a value less than about 20%;

a uniform etch-stop $Si_{1-y}Ge_y$ layer of with a selected thickness where the Ge composition y larger than about 20%; and

a second compositionally graded $Si_{1-z}Ge_z$ buffer where the Ge composition x is decreasing from about 20% to a value less than 20%.

20. A method of fabricating a semiconductor structure comprising:

providing a first semiconductor substrate;

depositing a first compositionally graded $Si_{1-x}Ge_x$ buffer on said first semiconductor substrate, where the Ge composition x is increasing from about zero to a value less than about 20%;

depositing a first etch-stop $Si_{1-y}Ge_y$ layer of on said first compositionally graded $Si_{1-x}Ge_x$ buffer where the Ge composition y is larger than 20% so that the layer is an effective etch-stop; and

depositing a second etch-stop layer of strained Si.

21. The method of claim 20 further comprising depositing one or more material layers before depositing said second etch-stop layer, said one or more material layers are selected from a group consisting of, but not limited to, a compositionally graded $Si_{1-z}Ge_z$ buffer where the Ge composition z is increasing from about 20% to a value much higher than 20%, a second compositionally graded $Si_{1-z}Ge_z$ buffer where the Ge composition z is decreasing from about 20% to a smaller value, a relaxed $Si_{1-z}Ge_z$ layer, a strained $Si_{1-x}Ge_x$ layer, where Ge composition x is a value between 0 and 1, a GaAs layer, a III-V material layer, and a II-VI material layer.

22. The method of claim 20 further comprising polishing the surface of one of said deposited layers.

23. A semiconductor etch-stop layer structure comprises:

a monocrystalline semiconductor substrate;

a compositionally graded $Si_{1-x}Ge_x$ buffer, where the Ge composition x is increasing from about zero to a value less than about 20%;

a first etch-stop $Si_{1-y}Ge_y$ layer where the Ge composition y is larger than about 20%; and

a second etch-stop layer of strained Si.

24. The structure of claim 23 further comprising, between said first and second etch-stop layers, one or more material layers selected from the group consisting of, but not limited to, a compositionally graded $Si_{1-z}Ge_z$ buffer where the Ge composition z is increasing from about 20% to a value much higher than 20%, a second compositionally

smaller value, a relaxed $Si_{1-y}Ge_y$ layer, a strained $Si_{1-z}Ge_z$ layer, where Ge composition y is a value between 0 and 1, a GaAs layer, a III-V material layer, and a II-VI material layer.

25. A method of fabricating a semiconductor structure comprising:

providing a first semiconductor substrate;

depositing a first compositionally graded $Si_{1-x}Ge_x$ buffer on said first semiconductor substrate, where the Ge composition x is increasing from about zero to a value less than about 20%;

depositing a first etch-stop $Si_{1-y}Ge_y$ layer on said first compositionally graded $Si_{1-x}Ge_x$ buffer where the Ge composition y is larger than about 20% so that the layer is an effective etch-stop;

depositing a second etch-stop layer of strained Si;

bonding said deposited layers to a second substrate;

removing said first substrate to release said first etch-stop $Si_{1-y}Ge_y$ layer ;

removing said remaining structure to release said second etch-stop layer; and

processing said released second etch-stop layer.

26. The method of claim 25 further comprising depositing one or more material layers before depositing said second etch-stop layer, and said one or more material layers are material layers selected from the group consisting of, but not limited to, a compositionally graded $Si_{1-z}Ge_z$ buffer where the Ge composition z is increasing from about 20% to a value much higher than 20%, a second compositionally graded $Si_{1-k}Ge_k$ buffer where the Ge composition k is decreasing from about 20% to a smaller value, a relaxed $Si_{1-z}Ge_z$ layer, a strained $Si_{1-o}Ge_o$ layer, where Ge composition o is a value between 0 and 1, a GaAs layer, a III-V material layer, and a II-VI material layer.

27. The method of claim 25 further comprising, before bonding, depositing one or more material layers selected from the group consisting of, but not limited to, a relaxed $Si_{1-z}Ge_z$ layer, a strained $Si_{1-z}Ge_z$ layer, where Ge composition z is a value between 0 and 1, a GaAs layer, a III-V material layer, and a II-VI material layer.

28. The process of claim 25, wherein said second substrate has an insulating layer on the surface.

29. The method of claim 25 further comprising depositing an insulating layer before bonding.

30. The method of claim 25 further comprising polishing the surface of one of said deposited layers.

31. The method of claim 25 further comprising polishing the surface of said first substrate before bonding.

32. The process of claim 25 further comprising depositing one or more second material layers selected from the group consisting of, but not limited to, relaxed $Si_{1-y}Ge_y$ layer, strained $Si_{1-z}Ge_z$ layer, strained-Si, Ge, GaAs, III-V materials, and II-VI materials, where Ge compositions y and z are values between 0 and 1.

33. The process of claim 32 further comprising polishing the surface of said one or more layer before depositing said one or more second material layers

34. The process of claims 25 further comprising fabricating a semiconductor device selected from the group consisting of, but not limited to, FET device, MOSFET device, MESFET device, solar cell device, and optoelectronic device.

35. A semiconductor structure having a layer in which semiconductor devices are to be formed, said semiconductor structure comprises:

a substrate;

an insulating layer;

a relaxed SiGe layer where the Ge composition is larger than approximately 15%; and

a device layer selected from a group consisting of, but not limited to, strained-Si, relaxed $Si_{1-y}Gey$ layer, strained $Si_{1-z}Ge_z$ layer, Ge, GaAs, III-V materials, and II-VI materials, where Ge compositions y and z are values between 0 and 1.

36. The structure of claim 35, wherein said substrate is a Si substrate.

37. The structure of claim 35, wherein said insulating layer is an oxide.

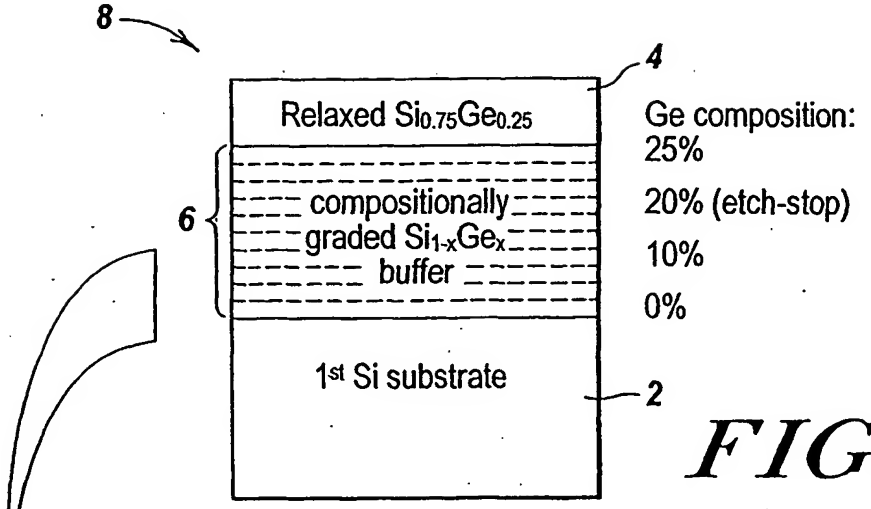
8
4
Relaxed $Si_{0.75}Ge_{0.25}$
Ge composition:
25%
6
compositionally
graded $Si_{1-x}Ge_x$
buffer
20% (etch-stop)
10%
0%
1st Si substrate
2

FIG. 1A

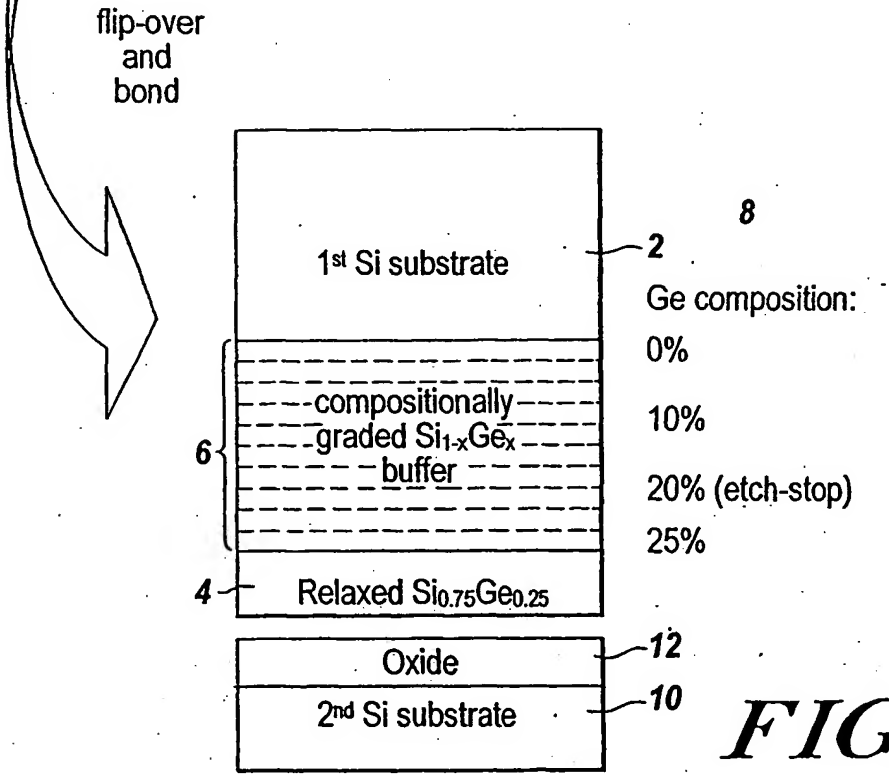
flip-over
and
bond
8
1st Si substrate
2
Ge composition:
0%
6
compositionally
graded $Si_{1-x}Ge_x$
buffer
10%
20% (etch-stop)
25%
4
Relaxed $Si_{0.75}Ge_{0.25}$
12
Oxide
10
2nd Si substrate

FIG. 1B

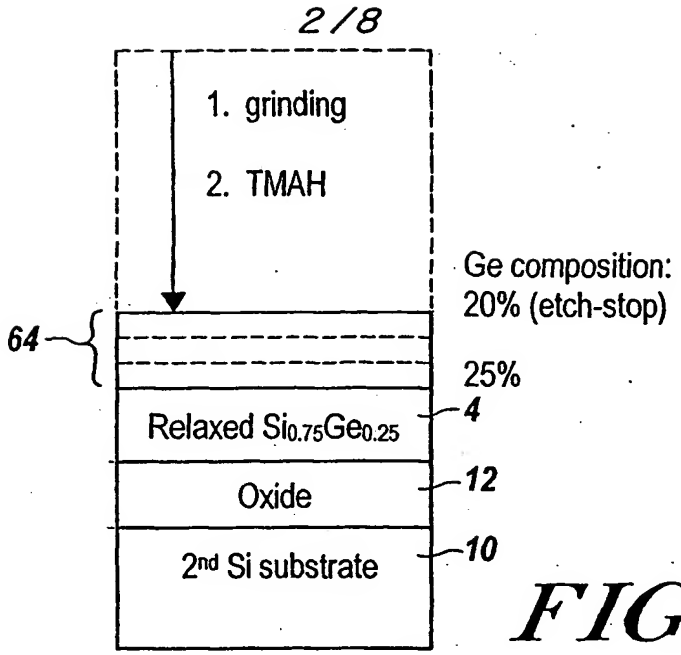

FIG. 1C

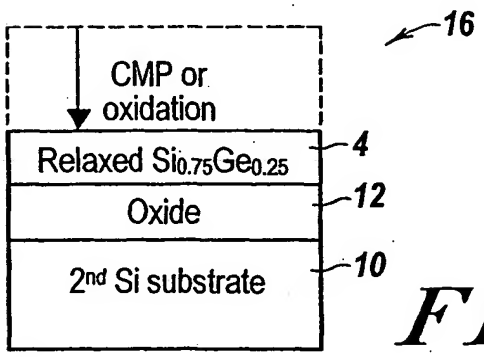

FIG. 1D

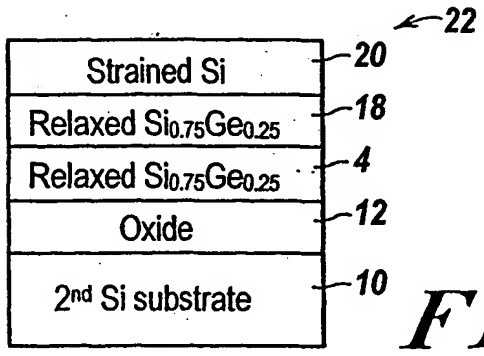

FIG. 1E

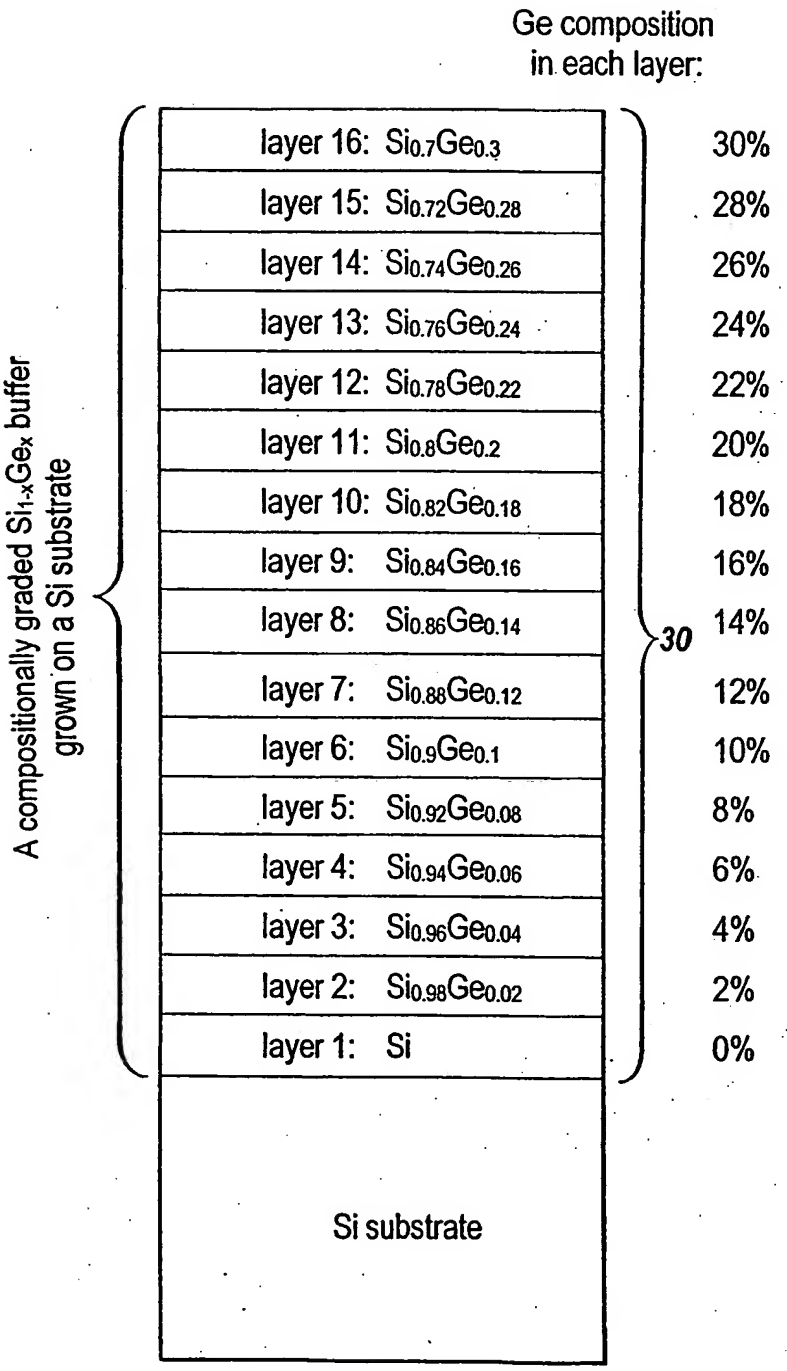
Ge composition in each layer:
layer 16: $Si_{0.7}Ge_{0.3}$ 30%
layer 15: $Si_{0.72}Ge_{0.28}$ 28%
layer 14: $Si_{0.74}Ge_{0.26}$ 26%
layer 13: $Si_{0.76}Ge_{0.24}$ 24%
layer 12: $Si_{0.78}Ge_{0.22}$ 22%
layer 11: $Si_{0.8}Ge_{0.2}$ 20%
layer 10: $Si_{0.82}Ge_{0.18}$ 18%
layer 9: $Si_{0.84}Ge_{0.16}$ 16%
layer 8: $Si_{0.86}Ge_{0.14}$ 14%
layer 7: $Si_{0.88}Ge_{0.12}$ 12%
layer 6: $Si_{0.9}Ge_{0.1}$ 10%
layer 5: $Si_{0.92}Ge_{0.08}$ 8%
layer 4: $Si_{0.94}Ge_{0.06}$ 6%
layer 3: $Si_{0.96}Ge_{0.04}$ 4%
layer 2: $Si_{0.98}Ge_{0.02}$ 2%
layer 1: Si 0%
30
A compositionally graded $Si_{1-x}Ge_x$ buffer grown on a Si substrate
Si substrate

FIG. 2

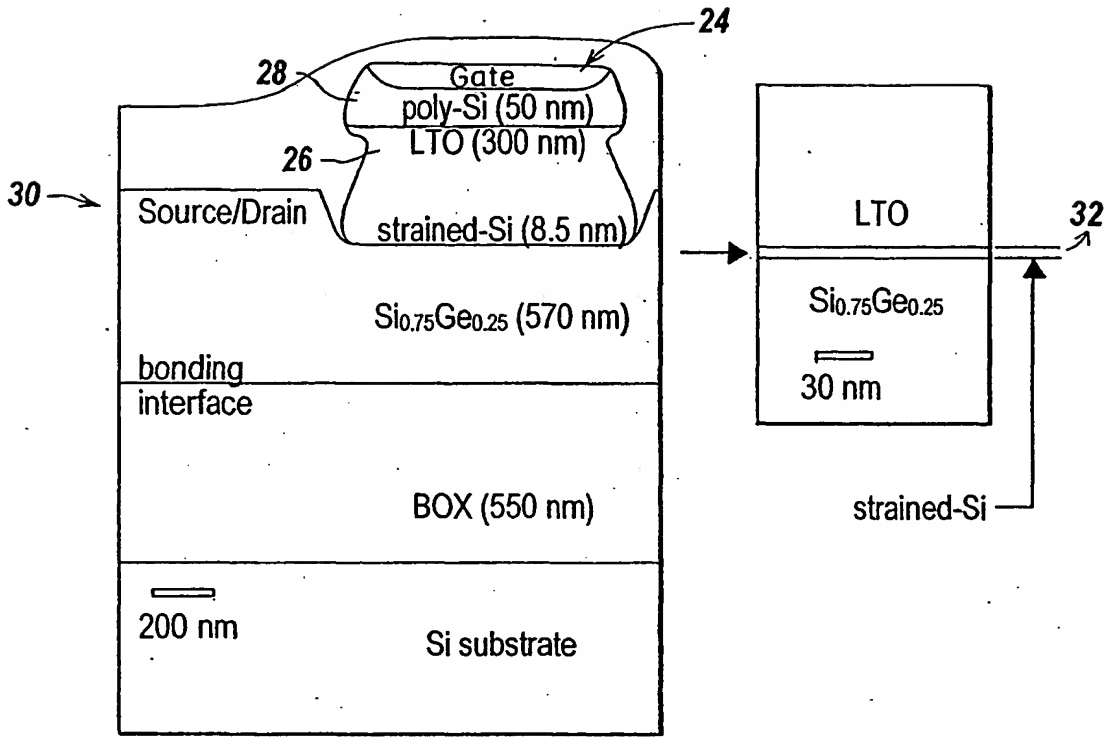
24
28
Gate
poly-Si (50 nm)
LTO (300 nm)
26
30
Source/Drain
strained-Si (8.5 nm)
Si0.75Ge0.25 (570 nm)
bonding
interface
BOX (550 nm)
200 nm
Si substrate
LTO
32
Si0.75Ge0.25
30 nm
strained-Si

FIG. 3

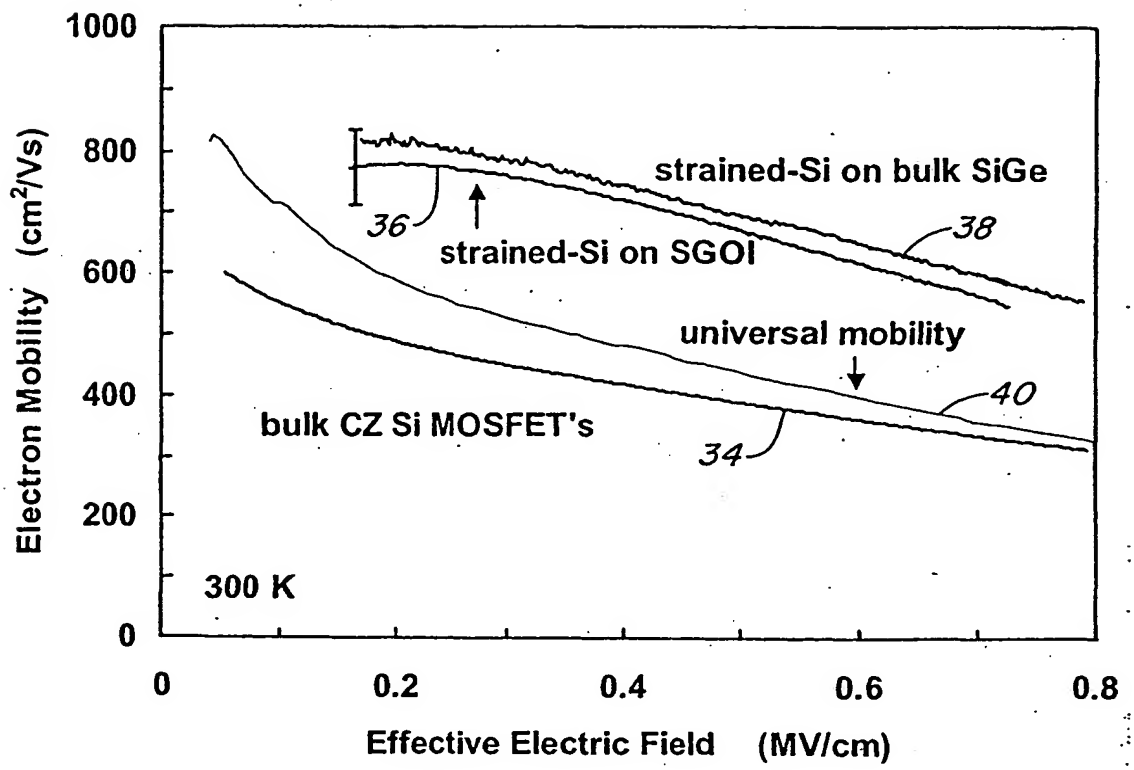
1000
800
600
400
200
0
Electron Mobility (cm²/Vs)
0
0.2
0.4
0.6
0.8
Effective Electric Field (MV/cm)
strained-Si on bulk SiGe
strained-Si on SGOI
universal mobility
bulk CZ Si MOSFET's
300 K
36
38
40
34

FIG. 4

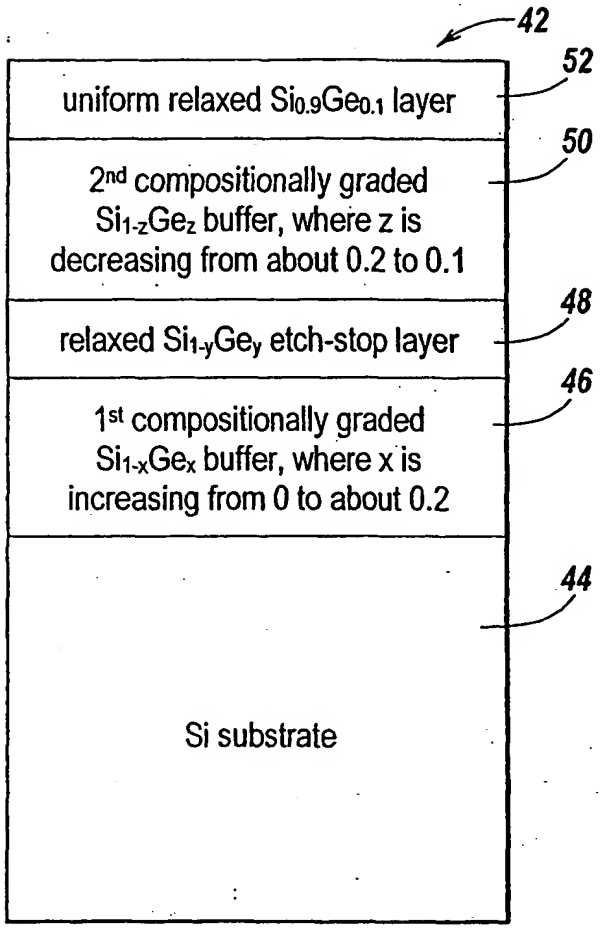
42
52
uniform relaxed $Si_{0.9}Ge_{0.1}$ layer
50
2nd compositionally graded $Si_{1-z}Ge_z$ buffer, where z is decreasing from about 0.2 to 0.1
48
relaxed $Si_{1-y}Ge_y$ etch-stop layer
46
1st compositionally graded $Si_{1-x}Ge_x$ buffer, where x is increasing from 0 to about 0.2
44
Si substrate

FIG. 5

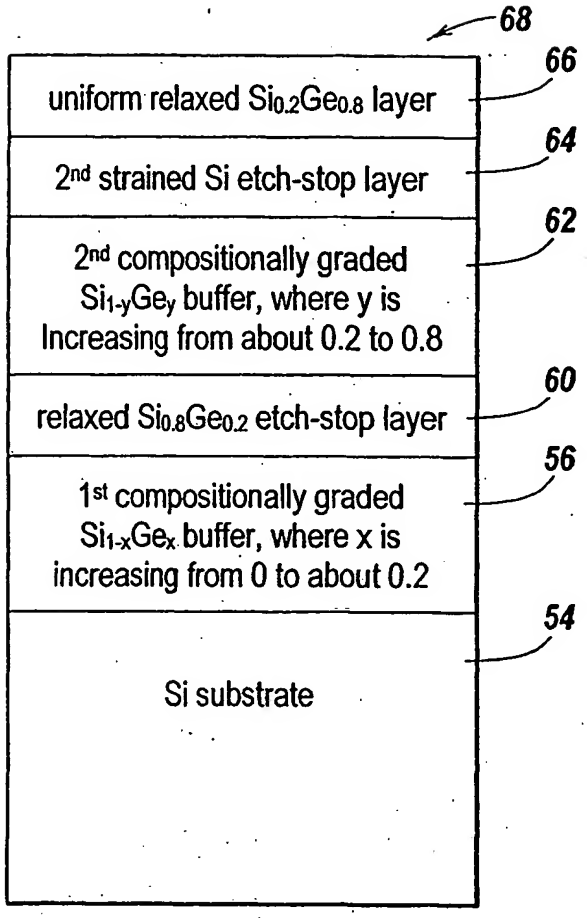
68
66
uniform relaxed $Si_{0.2}Ge_{0.8}$ layer
64
2nd strained Si etch-stop layer
62
2nd compositionally graded $Si_{1-y}Ge_y$ buffer, where y is Increasing from about 0.2 to 0.8
60
relaxed $Si_{0.8}Ge_{0.2}$ etch-stop layer
56
1st compositionally graded $Si_{1-x}Ge_x$ buffer, where x is increasing from 0 to about 0.2
54
Si substrate

FIG. 6

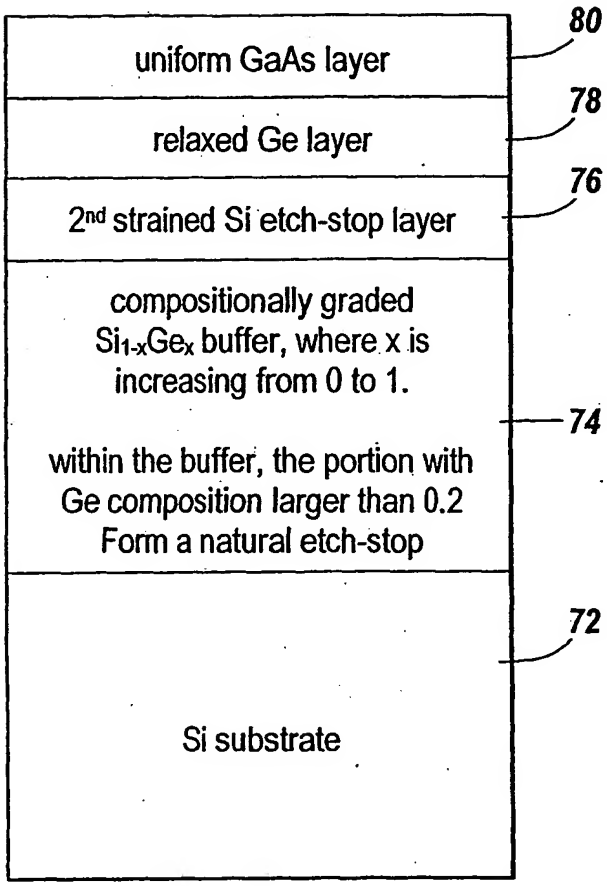
uniform GaAs layer
80
relaxed Ge layer
78
2nd strained Si etch-stop layer
76
compositionally graded
Si1-xGex buffer, where x is
increasing from 0 to 1.
within the buffer, the portion with
Ge composition larger than 0.2
Form a natural etch-stop
74
72
Si substrate

FIG. 7

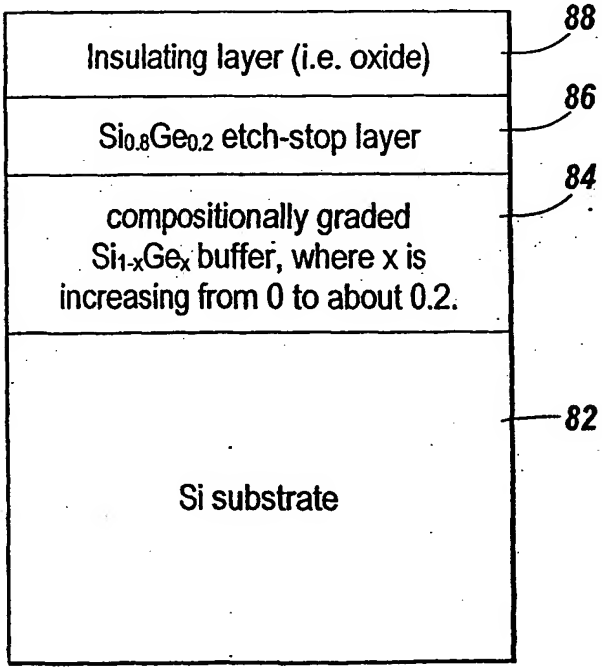
Insulating layer (i.e. oxide)
88
Si0.8Ge0.2 etch-stop layer
86
compositionally graded
Si1-xGex buffer, where x is
increasing from 0 to about 0.2.
84
82
Si substrate

FIG. 8

INTERNATIONAL SEARCH REPORT

ıtional Application No
PCT/US 02/10317

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H01L21/20 H01L21/762

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H01L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)
EPO-Internal, INSPEC, WPI Data, PAJ, IBM-TDB

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 99 53539 A (MASSACHUSETTS INST TECHNOLOGY) 21 October 1999 (1999-10-21) abstract; claims; figures 1A-1D,10	1-3,6
X	US 6 059 895 A (CHU JACK OON ET AL) 9 May 2000 (2000-05-09) abstract; claims; figures	1-3,6,8, 9,11-13, 16, 18-21, 23-29, 32,34-37
Y		4,5,7, 10,14, 15,17, 30,31,33

-/--

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
16 September 2002	23/09/2002

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax (+31-70) 340-3016	Wirner, C

Form PCT/ISA/210 (second sheet) (July 1992)

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	WO 98 59365 A (MASSACHUSETTS INST TECHNOLOGY) 30 December 1998 (1998-12-30) abstract; claims; figures page 2, line 7 - line 10 page 5, line 5 - line 10	4,5,7, 10,14, 15,17, 30,31,33
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A	EP 0 683 522 A (IBM) 22 November 1995 (1995-11-22) abstract; claims; figures 2,3 column 8, line 11 - line 20	1,9,11, 19,20, 23,25,35
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